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Rapidly measured predictors for the dry milling performance of corn

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by

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TABLE OF CONTENTS

LIST OF SYMBOLS

AG3_ = Agtron Reflectance, Wide Viewer:
- _W_ = Whole kernel sample (Data set A only)
- _G_ = Ground sample (Data set A only)
- _B = Blue filter
- _G = Green filter
- _R = Red filter
- _Y = Yellow filter

AG5_ = Agtron Reflectance, Narrow Viewer:
- _W_ = Whole kernel sample (Data set A only)
- _G_ = Ground sample (Data set A only)
- _B = Blue filter
- _G = Green filter
- _R = Red filter
- _Y = Yellow filter

DEN = Density
HARD = % Horneous endosperm
HES = Hard Endosperm Score
H_2O = Moisture by vacuum oven
HR_ = Hunter L Reflectance values
- _G = Ground Sample
- _W = Whole kernel sample

IDEN = Density index
INST = Instron

NIR_ = Near Infrared Reflectance:
- _S = Starch
- _P = Protein
- _O = Oil
- _W = Moisture

NIT_ = Near Infrared Transmittance:
- _S = Starch
- _P = Protein
- _O = Oil
- _W = Moisture

PDEN = Density by air pycnometer
SAMP = Sample ID.
TEX = Texturegage
THINS = % thins
YFG = Yield of flaking grits

INTRODUCTION

The History of Corn Dry Milling

The history of corn and corn milling goes back thousands of years. Investigators have reported finding specimens of corn in caves in southern regions of the North American continent (Mangelsdorf et al., 1967). Evidence of the first corn milling was described by Belt (1928), who observed that the ancient Indians of Nicaragua buried corn-grinding stones along with their dead for use in their next life.

In the pioneer days, early settlers used a handheld stone to grind corn in a concave bedstone. This method of grinding corn imitated the Indian metate. The next development was the hominy block which was made from a giant log pestle tied to a springy branch of a tree, and a hollowed wooden stump. The corn was placed in the stump and repeatedly hit with the pestle. These were eventually replaced with a device called a kwern, which consisted of a capstone which was rotated on a basestone. The corn was poured into a hole at the top, was ground by the turning action of the capstone, and fell out at the edges. This system increased in size to become a grist mill. Most grist mills gave way in the early 1900's to tempering-degerming systems (Larsen, 1959), which form the majority of corn dry mills.

The Corn Kernel

Structure

The basic structure of a corn kernel is shown in Figure 1. The corn kernel is a fruit that is composed of a pericarp surrounding a single seed. Beneath the pericarp lies the aleurone layer. Endosperm cells, the majority of the kernel (about 85% by weight), are filled mainly with starch granules. The germ, or embryo, composes about 10% of the kernel weight. Different kernel types exist, and are usually grouped as Dent, Flint, Flour, Sweet, Pop, and Pod. This project deals with dent corn, which is recognized by its vitreous, horny endosperm at the sides and back of the kernel, and its floury endosperm in the core and crown. On drying, the center of the crown collapses to give an indentation, the size of which varies with hybrid. The horny and floury endosperms are often referred to as `hard' and `soft' endosperms, respectively. The dent corn grown in the U.S. corn belt is mainly yellow; white dent corn is only around 3% of corn grown in the United States (Zuber and Darrah, 1987).

Importance to dry millers

To corn dry millers the most important property of corn is the percentage of hard, horny endosperm (H. Frost, Illinois Cereal Mills, Paris, IL, personal communication, 1991). The corn dry miller produces grits for food processors, which, in turn, are processed into breakfast cereals, snack foods, pancake flours, muffin flours, and alcohol.

Domestic use of corn for industrial and food products is comparatively small when compared with the volume used annually for animal feed. Only around 20% of the total corn grown in the U.S. is used for food and industrial purposes, and less than 20% of that is dry milled (Table 1). As only 3-4% of U.S. corn is dry milled, it is hard to encourage varieties to be grown to suit the dry miller (H. Frost, Illinois Cereal Mills, Paris, IL, Personal communication).

Corn dry millers prefer maximum separation of the endosperm, bran, and germ, with a high proportion of the endosperm being recovered as large flaking grits. Conditioning (or tempering) and degerminating processes separate the corn kernels into three fractions - bran, germ, and endosperm. The endosperm fraction should be low in fat, as most of the oil is in the germ fraction. This condition will ensure a long shelf-life for the endosperm fraction.

The physical properties of the corn kernel affect the yield of large flaking grits and other products. For maximum yield of large flaking grits, large kernels with a high proportion of hard endosperm and a low number of stress cracks are required. Kernels which more easily

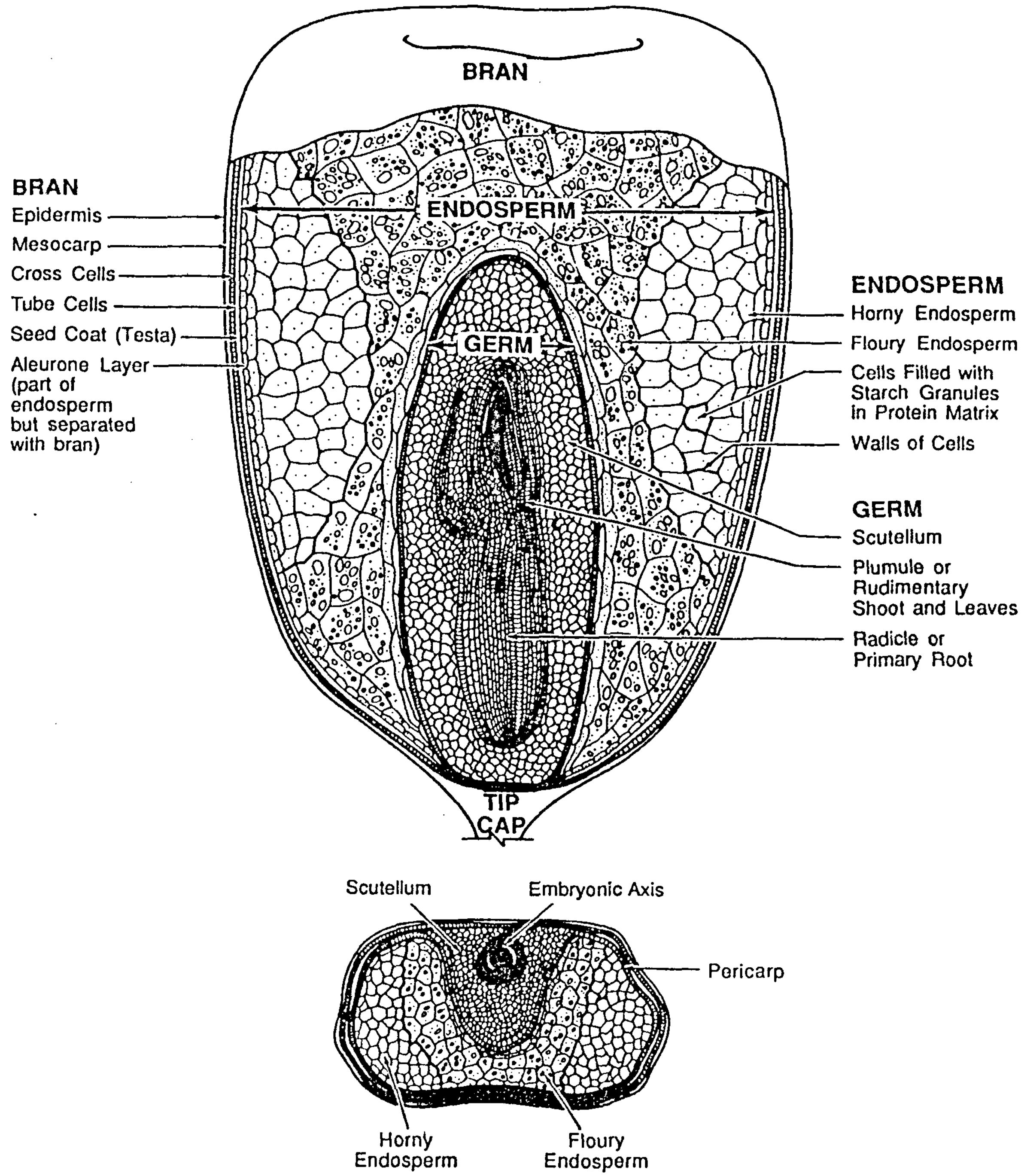

Figure 1. The anatomical structure of the corn kernel [Reprinted with permission from Johnson, L.A. (1991). Originally modified from figures provided by the Corn Refiners' Association, Washington, DC.]

Table 1. Food and industrial corn usage by volume (million bu.), United States, 1980, 1984, and 1989.

Year beginning Sept 1	1980	1984	1989[a]
Breakfast foods	31	34	-
Other dry milled products[b]	51	142	161[c]
Wet milled products	476	645	598
Alcohol	75	240	385
Total food and industrial use	733	1061	1286
Domestic use of products	715	1046	-
Export of products	18	15	-
Seed	20	19	19
Feed and Residual	4133	4117	4455
Total domestic use	4868	5182	5745
Exports	2355	1838	2367
Total	7223	7020	8113

[a]1989 data from USDA (1990) and USDA (1991). Some data not available.
[b]Estimated quantities used in processing flour, cornmeal, hominy grits, brewers grits, and flakes.
[c]Data for total dry-milled and alkaline-cooked products.
Adapted from Leath and Hill (1987).

allow the germ to be separated from the endosperm are of increased value, as are those with smaller percentages of bran. Many of the physical properties of corn are genetically determined.

Most dry millers buy their corn from the market as U.S. No.2 corn, although some contract with growers to control the hybrids and production practices used. When buying from the market, the dry miller needs a guarantee that corn will be high yielding in the more valuable products. Meeting this goal requires dependable tests that will relate to the yield of endosperm from dry milling. Many millers are still searching for reliable measurements of kernel characteristics that provide the best prediction of product yield (H. Frost, Illinois Cereal Mills, Paris, IL, personal communication, 1991).

The Dry Milling Process

A corn dry mill processes corn by mechanical separation of the kernel into various fractions, which are sifted, classified, and sized. Corn kernels must withstand various abrasion and mechanical procedures. To obtain the desired final dry milled products, millers should receive corn that contains a preponderance of hard endosperm, because soft endosperm will not withstand the mechanical dry milling process.

The dry milling process using the Beall degerminator

The Beall degerminator was first introduced in 1906 (Larsen, 1959), and has remained the mainstay for most U.S. dry millers who use a tempering-degerming system (Alexander, 1987). It has brought about the centralization of mills with increased capacity and more efficient processing.

Corn is first screened to remove foreign material and broken kernels, so that only whole corn remains. The corn is then wet cleaned to remove dust and dirt, and conditioned to about

20% moisture in a tempering bin to toughen and loosen the bran and germ from the endosperm for easier separation in the degerminator.

A degerminator is a horizontal, cone-shaped drum, with small projections of metal on the outside. The drum rotates within a metal housing, which also has metal projections, and is covered with perforated screens. Corn enters the small end of the drum, and as it proceeds to the large end, the bran and germ separate from the endosperm. The smaller, lighter particles, which mainly consist of the separated germ and bran, pass through the screens and are collected as "throughstock", while the larger pieces pass out of the end of the drum. The latter are called "tailstock". Tailstock is the large grits of hard endosperm.

Further grinding, screening, and aspiration take place on the throughstock and tailstock. These processes are to separate the endosperm into fractions of various sizes. Also, the germ and bran are separated. The bran becomes livestock feed. Oil can be extracted from the germ, and the remaining cake is ground into germ flour or used as feed.

Other methods employed in dry milling

Alternative dry milling systems that are used to produce refined dry-milled corn products include the Ocrim and Buhler-Miag processes, which were developed in Europe (Alexander, 1987). Other methods of degerming or milling corn include a variety of hammer, roller, and pin mills. In some cases degerming is not necessary, and the corn is simply ground. The preferred method of milling is determined by the end use of the corn.

The Quality and Value of Dry Milled Products

The various products of the dry milling process are valued differently. Large flaking grits obtain the highest price, meal and flour are of intermediate value, and feed is usually the lowest priced. Oil is often priced more than twice the value of large flaking grits, but has only a small yield (Hill et al., 1991).

The value of the grits from the endosperm is directly related to their size. The size of these grits is classified by the number of screen wires per inch. Many products are possible; from large flaking grits, which can be as course as four-mesh, to as small as flour, which may pass through a 100-mesh sieve. However, all of these products fall into six main categories, shown in Table 2.

A large grit can only result if there is a large amount of hard endosperm in the kernel being milled. This hard endosperm must remain intact through the degermination process. The

Table 2. A typical range of products from a corn tempering-degerming system.

	Product size				Percent of products
	From		To		
	U.S. Mesh	µm	U.S. Mesh	µm	
Flaking grits	-3.5[a]	-5600	+6[b]	+3350	20
Coarse grits	-10	-2000	+15	+1290	25
Regular grits	-15	-1290	+30	+600	36
Cornmeal	-30	-600	+60	+250	5
Corn cones	-40	-425	+80	+180	5
Corn flour	-60	-250	+325	+45	9

[a]A negative number indicates the maximum size screen the fraction passes through.
[b]A positive number indicates the minimum size screen the product is retained upon.
Adapted from Alexander, 1987.

miller prefers large kernels with high percentages of hard endosperm, and few stress cracks. The size of the kernel and percentage of hard endosperm are determined by genetics and growing conditions. The extent to which the hard endosperm stays intact is a function of handling practices and drying techniques.

The percentage of fat also partly determines the quality of flaking grits: the higher the fat content, the lower the quality of the grits, due to the tendency to develop oxidized flavors and odors. Germ- and bran-free products have a greater stability and shelf-life.

Economic Importances

The value of corn to the dry miller depends on the yields of different products and their relative prices. Demand and price for different dry-milled products are subject to change, so the dry miller may need to alter operating parameters and settings in order to accommodate these changes. Therefore, it is not easy to determine the value of an increase in yield of large flaking grits, as this increase means the decrease in other products, which may be in demand at the time. Large grits can always be reduced, but this extra step is an added cost to the miller. The value of the corn to the miller, that is to say, the profit he will make, is controlled by (1) initial cost, (2) the prices of the different products, (3) the yield of each product, and (4) the operating and milling costs (Hill et al., 1991). The mill settings and the cost of milling different qualities of corn with these different settings are hard to calculate, and are often assumed as constants when considering economic models.

Hill et al. (1991) developed equations to predict value based on quality. It must be pointed out, however, that different equipment may vary in output, and hence the methodology employed for the predictor equations would have to be applied to the individual equipment.

There are currently many tests that claim reasonable correlations with hardness in corn. However, only a small amount of the literature goes beyond simple correlation to models for predicting hardness. Models may be able to cover several aspects of corn which ultimately determine the way in which corn will act in a dry mill, and hence predict potential yields from a sample.

LITERATURE REVIEW

Product Yield Predictors and Determinants

The testing which takes place on corn in the marketplace and in the mill must be rapid and reliable, and a good predictor of the yields of the primary products. Many tests have been developed and used to this end, but at this time, none are completely reliable, and none are widely used. Some companies prefer to keep their testing methods proprietary (H. Frost, Illinois Cereal Mills, Paris, IL, personal communication 1991).

A milling evaluation factor (MEF), representing the yields of desired products, was found from a procedure designed to duplicate an actual commercial corn dry mill. This evaluation was carried out in a pilot plant or laboratory. The method described by Stroshine et al. (1986) involved conditioning the corn to 24% moisture, before it was degermed in a horizontal drum degerminator. After screening and aspiration, the remaining material was dried to 17% moisture and passed through a sieve stack containing 3.5-, 5-, 7-, 10-, and 16-mesh sieves. The resulting fractions were further aspirated and suspended in sodium nitrite solution (specific gravity 1.275) to remove any remaining germ. The fractions of endosperm were dried and weighed. An equation assuming that the 3.5-, 5-, and 7-mesh fractions represented the desired products from a dry mill, provided a numerical expression for the results of their dry milling process:

$$\text{MEF} = [E_{3.5\text{-mesh}} + E_{5\text{-mesh}} + E_{7\text{-mesh}}]\,[E_{\text{Total}}/100]$$

Where E = Percentage of total endosperm weight retained on the screen identified by the subscript

E_{Total} = Percentage of total sample recovered in all endosperm products

Factors which need to be recognized in order to come closer to identifying a test for product yield include: the kernel size, the percentage of the kernel which is hard endosperm, and the resistance of the endosperm to breakage.

Many tests developed measure density. These include test weight, bulk density, ethanol column density, and floaters (Hill et al., 1991, Pomeranz et al., 1984, 1985, 1986a, b). The bulk density measurement, along with the other density related measurements of corn, has been shown to positively correlate with the yields of the more favored dry milled products. Although test weight can significantly correlate with hard endosperm content of corn, other factors may be involved, which reduce the reliability of test weight alone.

Tests that measure kernel size, such as kernel length, and percentages retained by screens, are often important factors in determining flaking grit yield (A. B. Roskens, USGP Purchasing, Barrington, IL, Personal Communication, 1991). This relationship is obvious, as one cannot get large grits from small corn kernels! However, these tests alone may ignore the important factor of breakage susceptibility.

Stress cracks cause kernels to fracture upon impact. Visual quantification of stress cracks is both slow and subjective. Corn breakage susceptibility tests have been developed that try to correlate with stress cracking (Watson, 1987). These include the Wisconsin breakage test (Singh and Finner, 1983), which is essentially an impact test, and the Stein breakage test (Miller et al., 1981), which also involves impacting the corn kernels.

The Stenvert test for hardness (Stenvert, 1974, Pomeranz and Czuchajowska, 1985) employs the time used to grind a sample, or the volume produced from grinding. Redding et al. (1990) showed that there was no relationship between the Stenvert hardness test and breakage susceptibility.

Beyond physical measurements, chemical analyses can also play an important role in MEF prediction. However, many of these analyses can be very complicated and take considerable time. The development of Near Infrared Reflectance (NIR) and Near Infrared Transmittance (NIT) has accelerated the rate of numerous chemical analyses from hours to seconds. The infrared data correlates well with standard proximate analyses (Barton and Cavanagh, 1988). The analyses are based on the different near infrared absorption bands of the components of the kernel. These bands are absorbed in proportion to the amount of the constituents present. There are some who argue that the chemical composition of the kernel has very little to do with how the kernel will behave under dry milling conditions. However, some researchers have found good correlations between NIR (and NIT) and other methods that may be used to predict MEF. Pomeranz et al. (1984) showed that NIR at 1680nm correlated well with hardness and density measurements. However, the post-harvest history of the grain was needed for interpreting the data. It was concluded that breakage susceptibility and hardness must both be considered for predicting how the corn would behave during milling. Pomeranz and Czuchajowska (1987) showed high correlations between flaking grits and test weight, and flaking grits and NIR at 1680nm.

Objective

The objective of this research was to conduct several tests that were readily available, and to use these to build models that could be used to predict the yield of flaking grits that would result from dry milling the corn.

MATERIALS AND METHODS

Three sets of samples were used in this research. Varying testing methods were used on each sample set, so to avoid confusion, these samples shall be referred to as sample sets "A", "B", and "C". From these sample sets were obtained data sets "A", "B", and "C", respectively. Sample sets A and B were used to explore various methods of evaluating corn hardness and milling yield. The most favorable methods were applied to sample set C.

Experimental

Sample set A

A dry miller supplied 76 samples of yellow No. 2 corn which previously had been graded visually for its hard endosperm content. Grade A was given for a high content of hard endosperm, grade B was given for lower hard endosperm content, and grade C was given for an unacceptably low content of hard endosperm (soft, floury corn). The corn had also been subjected to a pilot-scale milling test to supply the yield of flaking grits from 100 pounds, designated "Hard Endosperm Score" (HES).

Recognizing that visual observation may not be an objective test in predicting the physical characteristics of corn, further physical, chemical, and instrumental analytical tests were performed on the samples to explore any relationships between the physical and chemical characteristics of corn.

Agtron reflectance The Agtron M300 (wide area viewer) and Agtron M500 (small area viewer) reflectance instruments (Agtron, San Jose, CA) were used on both whole kernel and ground samples to measure relative spectral qualities. A Wiley mill (Arthur H. Thomas C^{o}. Scientific Apparatus, Philadelphia, PA) fitted with a 20-mesh screen was used to grind samples. The illumination sources in the Agtron units were mercury and neon discharge tubes. The units were calibrated with standards, where the black standard had a value of zero, and the white standard had a value of 90. The yellow (585nm), red (640nm), and blue (436nm) filters were used for the analysis of the samples which filled the small or wide area viewer sample containers. The sample containers were leveled before readings were taken.

Hunter Hunter L-values were taken for both whole and ground samples on the Hunter color difference instrument (Hunterlab Co., Fairfax, VA). Samples were ground using a Wiley mill. The Hunter color difference instrument was calibrated with black and white standard tiles, where black had a value of zero, and white had a value of 100. The light source was a DZA low voltage halogen cycle lamp, and a 10^{o} aperture was used.

Density index An index of density was measured by taking the weight of 250cc of corn. The corn was packed in a graduated cylinder, which was dropped three times on a table from a height of 5cm. The weight of the corn was corrected to 15.5% moisture. Results were reported in grams.

Moisture The vacuum oven method AACC #44-40 (AACC, 1984) was used to measure the moisture content of the corn. A Wiley mill was used to grind the samples. Although this method was not a rapid measure, this moisture reading was used to correct the density index to 15.5%.

From the total set of 76 samples, a subset of 30 samples was selected. The samples in this subset were chosen from all three visual grades, so that distinctively high, medium, and low contents of hard endosperm were present. The hard endosperm scores ranged from 62.7 to 39.7 (% yield of flaking grits by weight).

Near infrared reflectance (NIR) A set of NIR values were collected on ground samples of the subset of 30 samples using the Dickey-John Instalab-800 near infrared reflectometer (Dickey-John, Auburn, IL). The reflectometer gave values for moisture, protein, oil, and starch. (The latter three values were corrected to 15.5% moisture.) Samples were ground using a Magic Mill III Model 100 (Magic Mill, Salt Lake City, UT). The moisture values from these NIR readings were not used to correct the density index because they were not made at the same time as the density index.)

Sample set B

Forty-eight samples of white dent corn were provided by Quaker Oats Co., Cedar Rapids, IA. With these samples, Quaker provided the following results from their tests for hard endosperm content.

100 kernel weight One hundred whole representative kernels were randomly selected from the sample (damaged/end kernels, etc. were not included). The weight in grams was recorded.

100 kernel volume A 100-ml graduated cylinder was filled to 50ml with water. The previously selected and weighed 100 kernels were poured into the cylinder and the volume displaced was determined.

Density Density was found by dividing the weight of a 100 kernel sample by the volume of those same 100 kernels. The volume was found by placing 50ml of water in a 100-ml graduated cylinder, then measuring the volume displaced by the 100 kernels. The density (g/cm^3) was adjusted to 15% moisture using the following equation (Redding et al., 1990):

$$d_{kf} = d_{ki} - 0.00289\ (M_f - M_i)$$

Where d_{kf} and d_{ki} = final and initial kernel density

M_f and M_i = final and initial moisture level, %

Percent thins The corn sample was mixed to obtain uniformity. One hundred grams were weighed, and poured onto a 20/64" (2.5 mesh - 8mm) round hole sieve. The sieve was shaken 10 - 12 times, and the kernels that fell through were weighed. This number was designated % thins.

Percent horneous endosperm Ten to fifteen representative kernels were placed on a candling table with the germ face up. The kernel endosperm was visually separated into a more opaque, floury region across the top of the kernel, designated area 1, and the more translucent horneous regions at the sides, designated areas 2 and 3. The corn was judged between 70 and 95% horneous endosperm, depending on how large area 1 was.

Grit to germ ratio Ten to fifteen representative kernels were placed on a candling table with the germ face up, and visually inspected. If the germ face was ¾ or less of the kernel length and ½ or less of the width, then the kernel was judged to contain less than 30% germ (desirable).

In addition to the above tests provided by Quaker, the following tests were also performed to explore relationships between various physical and chemical characteristics of corn.

Near infrared transmittance (NIT) A set of NIT values were determined on samples of clean whole kernel corn using the Trebor-99 composition analyzer (Trebor, Gaithersburg, MD). The instrument gave values for moisture, protein, oil, and starch. Protein, oil, and starch values were adjusted to 15.5% moisture.

Texture-test system Seeking an objective measure of hardness, the Texture-test machine (or Texturometer), model T-1300G Texture Test System (Food Technology Corporation, Rockville, MD) was used with a 300psi (21.1kgfcm^{-2}) tension-compression load cell set at 250psi (17.5kgfcm^{-2}). A Kramer multi-blade shear cell (Bourne, 1982) was attached to the Texturepress. A sample of ten randomly selected kernels (not including damaged or end kernels,) were placed in the Kramer shear cell, and were crushed as the machine bit down on them. The Texturegage was set to hold the maximum peak, which was recorded and used as an index to hardness.

Sample set C

A dry miller supplied 14 samples of 1991 yellow No. 2 corn, which previously had been graded by a proprietary method. The corn was assigned values according to this method, and was also ranked from 1, for highest content of hard endosperm down to 14, for lowest content of hard endosperm (floury).

The following physical and instrumental analytical tests were performed on the samples.

Agtron reflectance The Agtron M300 (wide area viewer) reflectance instrument was used on whole kernel samples to measure relative spectral qualities, as described for data set A. The green (546nm) filter was used in addition to those previously mentioned.

Density Density was found by dividing the weight of a 100 kernel sample by the volume of those same 100 kernels, as described for sample set B.

Density by air pycnometer The Beckman Model 930 air compression pycnometer (Beckman Instruments Inc., Fullerton, CA.) was used to measure the volume of a sample of whole corn kernels. Air-comparison pycnometer procedures as described by Thompson and Isaacs (1967) were used. The density (g/cm^3) was calculated using the sample weight. The density was adjusted to 15% moisture using the equation given for density in sample set B.

Percent thins This value was obtained by weighing the amount of a 100g sample that fell through a 20/64" round hole sieve after shaking 12 times.

Instron The Instron universal testing machine, model 1122 (Instron Corporation, Canton, MA), with a 500-kg tension-compression load cell set to maximum (sensitivity = 50) was used. Ten randomly selected kernels were tested using the Kramer Shear press. All tests were conducted at a crosshead speed of 200mm/min. The recorder was operated at a chart speed of 500mm/min. A Zenith ZF-151-52 microcomputer (Zenith Electronics Corporation, Glenview, IL) equipped with an analog to digital converter processed the electronic output from the compression cell, and calculated the force/acceleration by a computer program. The maximum peak was used as an index to hardness.

Near Infrared Transmittance (NIT) NIT values for cleaned, whole kernel corn were collected for moisture, protein, oil, and starch (on a 15% moisture basis) as described for data set B.

Near infrared reflectance (NIR) NIR values were collected on ground samples of corn for moisture, protein, oil, and starch as described for data set A. The latter three values were based on 15% moisture.

Milling Evaluation The corn was subsequently subjected to a pilot-scale milling evaluation test on the equipment in the dry pilot plant in the Center for Crops Utilization Research (CCUR), at Iowa State University. About 1kg of corn was tempered to between 20.5 and 21.5% moisture by weight. Nine hundred grams of each tempered sample were degermed using the degerminator in the dry pilot plant. The product from the degerminator was fractionated for 30 minutes in the dry pilot plant rotary sieve (Great Western Manufacturing C^{O}. Inc., Leavenworth, KS.) containing 4-, 5-, 6-, 7-, 8-, 10-, and 22-mesh trays. The fractions retained on the 5- and 6-mesh trays contained pieces of germ, endosperm, and pericarp. The germ and pericarp were separated from the endosperm grits in these two fractions using a Kice aspirator (Kice Metal Industries, Wichita, KS). The aspirator was initially set to 180. The liftings were passed through twice more, first at 160, then at 140, to ensure a maximum yield of grits. Any germ or material that was not considered to be a flaking grit was removed by hand. The grits from each fraction were weighed. The combined weights of the two fractions were used to calculate the yield from 100g, which was designated the "Yield of flaking grits" (YFG).

Statistical

Statistical analysis of the data was carried out using the Statistix 4.0 program (Analytical Software, Saint Paul, MN). Simple correlations between all variables was used to look at individual correlation coefficients (r-values) with HES and YFG, as well as other correlations that may have had relevance.

Best subset regressions analyses were used to indicate the best predictive models for HES and YFG. The best subset regressions procedure computes the best subset regression models, given a full model that contains all the predictor values of interest. A specified number of the subset models with the highest R^2 are listed for each model size. The best three models for each number of variables included were displayed. The Mallow's statistic (Cp) and coefficient of determination (R^2) were used to evaluate and compare regression models. The Mallow's Cp is useful for model selection, and is based on the fact that not including an important variable in the model results in the fitted response values being biased. Cp gives an index of this bias. Good models have a Cp near or less than P, where P is the number of parameters in the model. This statistic was useful for eliminating variables that contributed little to the model, but told nothing about whether all the correct variables were present in the first place (Snedecor and Cochran, 1980). R^2 measures the proportion of variance in the dependent data explained by the regression.

Models selected using the above procedure were drawn using multiple regression analysis and their statistical significance was determined by analysis of variance. The regression coefficient tables gave the regression coefficients (slopes) associated with the independent variables and their standard errors, t-statistics, associated probability-values (p-values), and variance inflation factors (VIF). Probability-values were used to test whether the slopes were significantly different from zero. Large VIF's (7 or greater) indicated that colinearity was a problem in a model. The VIF shows the increase in variance of a coefficient due to correlation between the independent variables.

RESULTS AND DISCUSSION

Data Set A

Data set A contained 30 samples, and was reported on a 15.5% moisture basis. (The data is shown in Appendix B.) Simple correlation analysis for data set A (Table 3) showed that for the individual test parameters, the density index values showed the best correlation with HES (r-value of 0.70), and the NIR starch correlation with HES had an r-value of -0.66. The Agtron reflectance values for the narrow and wide area viewers read in the blue mode for ground samples had values of -0.69 and -0.66, respectively. This outcome shows that the blue end of the spectrum can be used as a measure of soft white starch (Johnson, 1965), which is undesirable for dry millers. Hard, endosperm is what dry millers need.

The best subset regression analysis for HES, which included density index, the NIR data, and the whole kernel data from the Hunter and Agtron instruments as the independent variables, suggested the combinations of variables in Table 4 to be the best models for the given variables in predicting HES.

The linear/multiple regression analysis and analysis of variance were used to look at individual p-values and cross correlation of variables within an equation in order to eliminate unreliable models. Equations 1 and 2 were the best models for the given variables for predicting HES.

Equation 1:

$$HES = -62.9 + 1.32*IDEN + 2.11*NIRP$$

$R^2 = 0.57$ SD = 4.23

Table 3. Simple correlations for individual test parameters with HES in data set A

Attribute	Hard Endosperm Score	Significance ($p \leq$)
Density index[a]	0.70	0.001
Hunter L-value		
Ground	-0.43	0.017
Whole	-0.50	0.005
Agtron		
Narrow		
Ground		
Blue	-0.69	0.001
Yellow	-0.38	0.037
Whole		
Red	-0.48	0.007
Yellow	-0.51	0.004
Wide		
Ground		
Blue	-0.66	0.001
Red	-0.44	0.015
Yellow	-0.53	0.002
Whole		
Blue	-0.42	0.022
Red	-0.40	0.027
Yellow	-0.40	0.028
NIR[a]		
Protein	0.42	0.022
Starch	-0.66	0.001

[a]15.5% moisture

n = 30

The full correlation matrix is shown in Appendix B.

Table 4. Models for HES suggested by the best subset regression procedure for IDEN, NIR data, and whole kernel data for the Agtron[a] and Hunter[a] instruments.

Variables	R^2	p[b]	Cp[c]
IDEN, NIRS	0.59	3	-0.2
IDEN, NIRP	0.57	3	0.9
NIRO, NIRS	0.57	3	1.0
IDEN, NIRO, NIRS	0.63	4	-0.4
IDEN, NIRP, NIRS	0.62	4	0.2

[a]These parameters do not appear in the table because they appeared in none of the best subset models.
[b]Number of parameters in the model.
[c]Mallow's Statistic.

Equation 2:

$$HES = 399 + 6.99*NIRO - 6.31*NIRS$$

$R^2 = 0.57$ SD = 4.24

(The full linear/multiple regression analysis and analysis of variance for Equations 1 and 2 are shown in Appendix B.)

A further best subset regression analysis indicated probable models in which density index, the NIR data, and the ground corn data from the Hunter and Agtron instruments were used as independent variables (Table 5). Linear/multiple regression analysis and analysis of variance were used to select Equation 3.

Table 5. Models for HES suggested by the best subset regressions procedure for IDEN, NIR data, and ground sample data for the Agtron and Hunter instruments.

Variables	R^2	P[a]	Cp[b]
IDEN, NIRS[c]	0.59	3	2.7
NIRS, AG5GB	0.58	3	3.4
IDEN, AG5GB	0.57	3	3.8
IDEN, NIRS, AG3GR	0.66	4	0.1
IDEN, NIRS, HRG	0.65	4	0.7
IDEN, NIRS, AG3GY	0.65	4	0.9

[a]Number of parameters in the model.
[b]Mallow's Statistic.
[c]This model was also selected in Table 4.

Equation 3:

$$HES = 266 - 3.19*NIRS - 0.772*AG5GB$$

$R^2 = 0.58$ SD = 4.19

(The full linear/multiple regression analysis and analysis of variance for Equation 3 is shown in Appendix B.)

The results showed a favorable set of equations that suggested, with further work, predictor equations for corn hardness should be of much use to corn dry millers in selecting shipments of corn to purchase.

When selecting a model for HES prediction, limiting the number of analyses needed is essential. Some otherwise significant equations were excluded because they included too many different tests, and were neither rapid nor practical.

Data Set B

Data set B, containing 48 samples of white corn, is shown in Appendix C. The purpose of this part of the study was to examine possible correlations between some rapidly performed tests. Table 6 shows the cross correlation matrix for the data.

The weight of 100 kernels gave a high correlation with the Texturometer readings. Percent thins was also correlated with the Texturometer. The texturometer readings are probably influenced by three factors. The percentage of hard endosperm present would be the major consideration, although kernel size in relation to the blade size of the Kramer shear cell, and stress cracks would also influence the measurement. Kernel size and stress cracks would explain why the texturometer correlated with the thins measurement, which measures size and possibly stress cracks (from broken kernels present). The Texturometer (or similar device,

Table 6. Correlation matrix for data set B[a].

	DEN	HARD	100KV	100KW	TEX	NIRO	NIRP	NIRS
HARD	0.12							
100KV	-0.21	0.08						
100KW	0.13	0.07	0.91					
TEX	0.21	0.27	0.43	0.50				
NIRO	-0.03	0.00	0.06	0.06	0.36			
NIRP	0.00	-0.07	-0.16	0.10	0.36	0.40		
NIRS	-0.05	0.06	0.17	0.09	-0.41	-0.43	-0.99	
THINS	-0.23	0.11	-0.21	-0.25	-0.44	-0.42	-0.61	0.65

[a]A correlation coefficient of 0.37 or greater gives a p-value of 1% or less.

such as Instron) alone may be a good instrument for measuring milling yield, because it would seem to be influenced by the above mentioned three factors. The percentage horneous endosperm did not correlate well with any of the other measurements, although this fact does not necessarily mean that the measurement would be of no use in milling yield predictor equations.

The Texturometer and percentage horneous endosperm measurements were used as indices of hardness for the purpose of analyzing the data. A best subset regression for each measure indicated no useful equations. A milling evaluation was not possible for this data set owing to small sample sizes.

Data Set C

The milling evaluation yield scores for the 14 samples ranged from 6.3 to 35.5 (% yield dry weight) where a score of 25+ gives an acceptable yield of flaking grits, a score of 20 to 25 is borderline, and a score of less than 20 indicates poor yield of flaking grits. (The data is shown in Appendix B.)

Simple correlation analysis (Table 7) showed that for the individual test parameters, the density values correlated best with the yield, with r-values of 0.96 for density by air pycnometer and 0.91 for the one hundred kernel method. The Instron measurements had a correlation of 0.84, which compares to other tests reported in the literature that try to measure breakage susceptibility. The Agtron Reflectance values for the wide area viewer had a high correlation, as did the NIT and NIR values for starch and protein. Protein positively correlated with the corn hardness and milling yields, whereas starch negatively correlated with hardness and milling yields. This outcome opposes the opinion held by some that say there is no relationship between the amounts of protein and starch present, and the yield of flaking grits (H. Frost, Illinois Cereal Mills, Paris, IL, personal communication, 1991).

Table 7. Simple correlations for individual test parameters with YFG in data set C

Attribute	Correlation With Milling Yield (YFG)	Significance (p <)
Density (Pycnometer)[a]	0.96	0.001
Density (100 Kernel)[a]	0.91	0.001
Agtron Wide Area Viewer		
Blue Filter	-0.65	0.012
Green Filter	-0.74	0.002
Red Filter	-0.81	0.001
Yellow Filter	-0.72	0.004
Near Infrared Reflectance (NIR)[a]		
Protein	0.83	0.001
Starch	-0.86	0.001
Near Infrared Transmittance (NIT)[a]		
Protein	0.69	0.006
Starch	-0.64	0.016
Instron	0.84	0.001

[a]15% moisture

n = 14

The full correlation matrix is shown in Appendix D.

The best subset regression analysis for yield of flaking grits using density by air pycnometer, percent thins, Instron, and NIT measurements produced the combinations of variables shown in Table 8.

Linear/multiple regression analysis and analysis of variance were used to look at individual p-values and cross correlation of variables within an equation in order to eliminate unreliable models. Equations 4 and 5 were the best models for the given variables for predicting YFG (full linear/multiple regression and analysis of variance appears in Appendix D).

Equation 4:

$$YFG = -285 + 239*PDEN$$

$R^2 = 0.92$ SD = 2.43

Table 8. Models for YFG suggested by the best subset regressions procedure using PDEN, NIT measurements, INST, and THINS.

Variables	R^2	P[a]	Cp[b]
PDEN	0.92	2	2.3
PDEN, THINS	0.95	3	0.3
PDEN, NITS	0.94	3	1.9
PDEN, INST	0.93	3	2.8
PDEN, NITS, THINS	0.95	4	1.4
PDEN, NITP, THINS	0.95	4	1.8
PDEN, INST, THINS	0.95	4	2.1

[a]Number of parameters in the model.
[b]Mallow's statistic.

Equation 5:

$$YFG = -293 + 249*PDEN - 0.125*THINS$$

$R^2 = 0.95$ SD = 2.09

The models including the variables PDEN, THINS, and NITP or NITS contained individual p-values for NITS/NITP that were too high for the lines of those parameters to be significantly different from zero.

The best subset regression analysis for yield of flaking grits using density by air pycnometer, percent thins, Instron, and NIR measurements produced the combinations of variables shown in Table 9.

Table 9. Models for YFG suggested by the best subset regressions procedure using PDEN, NIR measurements, INST, and THINS.

Variables	R^2	P[a]	Cp[b]
PDEN[c]	0.92	2	7.0
PDEN, THINS[c]	0.95	3	3.4
PDEN, INST[c]	0.93	3	6.9
PDEN, NIRS	0.91	3	8.9
PDEN, NIRS, THINS	0.95	4	5.0
PDEN, INST, THINS[c]	0.95	4	5.1

[a]Number of parameters in the model.
[b]Mallow's statistic.
[c]These models were also selected in Table 8.

There were no further useful equations from Table 9. Comparing the best subset regressions in Table 8 with those in Table 9, one can see that the NIT measurements are favored in relation to the Instron a little more than for the NIR measurements. This observation was supported by multiple regression which showed a lower p-value for equations containing NIT than those containing the corresponding NIR measurement. However, no equations containing Near Infrared data were significant (at the 1% level), owing mainly to the small data set size.

The best subset regression analysis for yield of flaking grits using density by air pycnometer, percent thins, Instron, and Agtron measurements produced the combinations of variables shown in Table 10. Multiple regression and analysis of variance showed no further useful equations from the parameters in Table 10, which suggests that the Agtron reflectometer was not a useful tool in milling yield prediction. However, the data set size was a limiting factor.

Although the Instron showed high correlation values with yield, it was of no use in predictor equations. Results were too variable as kernel orientation within the Kramer shear cell was important. Much work would be needed to be done for the Instron to become more reliable. A moisture correction equation is also needed. At the present, the Instron is not practical but worth investigation.

The predictor equations for YFG performed well when tested against the data used to construct them. Table E1 (Appendix E) shows the prediction values from Equations 4 and 5, and the actual yields. Appendix E also shows data from a 1992 sample set, and compares in Table E2 the actual yields with the predictions from Equations 4 and 5. The majority of the predictions were very reasonable. The corn used in the 1992 data set was not of the highest quality for corn dry millers, as indicated by the results from the milling yields and predictions.

Table 10. Models for YFG suggested by the best subset regressions procedure using PDEN, INST, THINS and Agtron measurements.

Variables	R^2	p[a]	Cp[b]
PDEN[c]	0.92	2	2.5
PDEN, THINS[c]	0.95	3	0.4
PDEN, INST[c]	0.93	3	2.9
PDEN, AG3B	0.93	3	3.7
PDEN, AG3R, THINS	0.94	4	1.2
PDEN, AG3Y, THINS	0.95	4	1.8
PDEN, AG3B, THINS	0.95	4	2.0

[a]Number of parameters in the model.
[b]Mallow's statistic.
[c]These models were also selected in Tables 8 and/or 9.

All of the samples were either borderline or too floury from visual observation. Much of the yields from the softest of the corn consisted of floury endosperm which remained intact on the flaking grits (which may explain why the predicted values were lower than the reported yields). This type of partitioning is not good, as it is mainly the properties of the hard endosperm which interest the processor who buys the flaking grits. With the above in mind, the low predicted yields may be a warning of the undesired composition of the grits, and thus be quite valid.

Equations 4 and 5 were improved to Equations 6 and 7, respectively, by including the test data from Appendix E to expand data set C.

Equation 6:

$$YFG = -261 + 220*PDEN$$

$R^2 = 0.93$ SD = 2.38

Equation 7:

$$YFG = -268 + 228*PDEN - 0.084*THINS$$

$R^2 = 0.96$ SD = 1.90

The most rapid of the tests employed in data set C were the air pycnometer density, percentage thins, and NIT, all of which were most useful in predictor equations.

In order for this research to be of value, we needed to see a dollar difference for the high, borderline, and low flaking grit yield as indicated by the yield of flaking grits (YFG) scores. Hill et al. (1991) used the entire product from the test mill to calculate the value of the corn, as well as for individual fractions. The relative demand of products must be considered in the calculations, otherwise results may be misleading, as total value does not accurately follow flaking grit value. In this case only the flaking grit fraction is considered, as this is the fraction that is of major dollar value to the dry miller, and most highly in demand (H. Frost, Illinois Cereal Mills, Paris, IL, personal communication, 1991). The total value of the corn may be improved by the lesser valued products; however their demand is not usually as high, and the miller may have to store the product, which adds to his cost. The average price of flaking grits from January to June, 1984, was \$0.12 (Hill et al., 1991), and was used in the calculations. Table 11 shows the variations in value of flaking grits per bushel of corn for the extended data set C. The high yield corn gave a range of values from around \$1.70 to \$2.40 per bushel. The borderline corn gave values of around \$1.30 to \$1.70, and the poor yield corn gave values of less than $1.30 per bushel. This analysis shows major dollar differences for the dry miller. The predictor equations gave reasonable estimations of value.

The high, borderline, and low yield corn ranges used here were cut off points drawn for the sake of this research. A dry miller may decide his own cut off points, and optimum values. Table 11 shows there was a clear dollar difference to the dry miller.

As with instrument calibration for reading corn kernel composition, data should be added year by year to create a larger and more reliable set of information that could be used to further improve models.

Table 11. Values of corn samples in data set C as calculated from actual yield of flaking grits, and YFG values from Equations 4 and 5.

Sample ID.	Predicted value ($/bushel) using		
	YFG	Equation 4	Equation 5
1[a]	2.38	2.42	2.30
2[a]	2.37	2.26	2.19
3[a]	1.86	2.20	2.13
4[a]	2.06	1.91	2.02
5[a]	1.81	2.12	2.05
6[a]	1.96	0.97	1.92
7[b]	1.50	1.44	1.37
8[a]	1.73	1.90	1.90
9[b]	1.65	1.51	1.63
10[b]	1.35	1.35	1.37
11[b]	1.57	1.52	1.63
12[c]	0.96	1.03	1.03
13[c]	0.81	0.94	0.85
14[c]	0.42	0.62	0.46
15[b]	1.52	1.39	1.31
16[c]	1.22	1.33	1.01
17[c]	1.21	1.44	1.22
18[c]	1.11	0.88	1.12
19[c]	1.03	0.92	0.96
20[c]	0.88	0.94	0.63
21[c]	0.65	0.46	0.64
22[c]	0.62	0.43	0.47
23[c]	0.35	0.44	0.19

[a]High yield corn (YFG $\leq$ 25).
[b]Borderline corn (20 $\leq$ YFG $<$ 25).
[c]Poor yield corn (YFG $<$ 20).

CONCLUSIONS

In general, the results showed that important parameters for dry milling predictions were:

(1) kernel size, as measured by percentage thins;

(2) composition (percentage hard endosperm), as measured by kernel density, or indirectly by Near Infrared analysis for starch, protein, oil, and moisture; and

(3) breakage susceptibility, as determined by the Instron with a Kramer Shear Cell.

The parameters mentioned above were combined in various ways to produce equations which would meet the criteria of rapidity and reliability. The best predictors determined by data set C were:

(1) density by air pycnometer; and

(2) density by air pycnometer and percent thins.

The limited data set size produced high R^2 and accompanying standard error values.

Measuring corn for size, percentage hard endosperm, and breakage susceptibility can give the corn dry miller estimates of large flaking grit yields. This research demonstrated that easily measured characteristics of market corn can be used to tell the dry miller if a particular lot of corn is suited to his requirements. The adoption of a test or series of analyses requires verification of the reliability of the test to predict the potential yield of the highest valued product produced by the mill. Rapidity and ease of performing the test are two vital criteria in its adoption. When selecting a model for yield of flaking grits, limiting the number of analyses which are needed to obtain the results is essential.

LITERATURE CITED

AACC. 1984. Approved Methods of the American Association of Cereal Chemists. 8th ed. American Association of Cereal Chemists, St Paul, MN.

ALEXANDER, R.J. 1987. Corn Dry Milling: Processes, Products, and Applications. In Corn: Chemistry and Technology, ed. WATSON, S.A., and RAMSTAD, P.E., 353. American Association of Cereal Chemists, Inc., St. Paul, MN.

ALEXANDER, R.J. 1973. Industrial Uses of Dry-Milled Corn Products. In Industrial Uses of Cereals, ed. POMERANZ, Y. American Association of Cereal Chemists, Inc., St. Paul, MN.

ANALYTICAL SOFTWARE. 1990. Statistix version 4.0 Users Manual. Analytical Software, St. Paul, MN.

AOAC. 1990. Official Methods of Analysis of the Association of Official Analytical Chemists. 15th ed. Association of Official Analytical Chemists, Washington, D.C.

BARTON, F.E. and CAVANAGH, G.C. 1988. The calibration of NIR reflectance spectrometer for the determination of diverse compositional parameters. J. Am. Oil Chem. Soc., 65 (5): 768.

BECKMAN INSTRUMENTS. 1971. Beckman Model 930 Air Compression Pycnometer Instructions. Beckman Instruments Inc., Fullerton, CA.

BELT, T., 1928. The Naturalist in Nicaragua. E. P. Dutton & Co., New York, NY.

BOURNE, M.C. 1982. Food Texture and Rheology: Concept and Measurement. Academic press, New York, NY.

BREKKE, O.L., WEINECKE, L.A., BOYD, J.N., and GRIFFIN, E.L. 1963. Corn Dry-Milling: Effects of First-Temper Moisture, Screen Perforation, and Rotor Speed on Beall Degerminator Throughput and Products. Cereal Chem., 40: 423.

ECKHOFF, S.R., PAULSEN, M.R., and LITCHFIELD, J.B. 1989. Processing the Right Corn. Illinois Research - Illinois Agricultural Experiment Station, Urbana, Illinois. The Station 31 (1/2) 8.

FOOD TECHNOLOGY CORPORATION. 1987. Operators Manual and Maintenance Information for the T-1300G Texturetest System. Food Technology Corporation, Rockville, MD.

FROST, H. 1991. Personal communication. Illinois Cereal Mills, Paris, IL.

HILL, L.D. 1991. Grain Quality Grading and Classification. Cereal Foods World, 36 (6): 491.

HILL, L., BENDER, K., PATTERSON, M., PAULSEN, M., BOUZAHER, A., and KIRLEIS, A. 1991. Economic Evaluation of Quality Characteristics in the Dry Milling of Corn. Bulletin 804, University of Illinois at Urbana-Champaign. OR North Central Regional Research Publication 330.

JOHNSON, L.A. 1991. Corn: Production, Processing, and Utilization. In Handbook of Cereal Science and Technology, ed. LORENZ, K. and KULP, K., Chap 2, Fig 1, p.57. Marcel Dekker, Inc., New York, NY.

JOHNSON, R.M. 1965. Light Reflectance Meter Measures Degree of Milling and Parboiling of Parboiled Rice. Cereal Chem., 42:167

HUNTERLAB CO. 1974. Instruction Manual for Hunterlab Digital Color Difference Meter D25D2A. Hunterlab Co., Fairfax, VA.

INSTRON CORPORATION. Universal Testing Machine, Model 1122. Instron Corporation, Canton, MA.

LARSEN, R.A. 1959. Milling. In Cereals as Food and Feed, ed. MATZ, S.A., 214. Avi Publishing Co., Westport, CT.

LEATH, M.N. and HILL, L.D. 1987. Economics of Production, Marketing, and Utilization. In Corn: Chemistry and Technology, ed. WATSON, S.A., and RAMSTAD, P.E., 201. American Association of Cereal Chemists, Inc., St. Paul, MN.

MANGELSDORF, P.C., MACNEISH, R.S., AND GALINANT, W.C. 1967. The Prehistory of the Tehuacan Valley, Vol. I. Univ. Texas Press, Austin, TX.

MANOHARKUMAR, B., GERSTENKORN, P., ZWINGELBERG, H., and BOLLING, H. 1978. On Some Correlations Between Grain Composition and Physical Characteristics to the Dry Milling Performance in Maize. J. Food Science and Technology, 15 (1): 1.

MILLER, B.S., HUGHES, J.W., ROUSSER, R., and POMERANZ, Y. 1981. Measuring the breakage susceptibility of shelled corn. Cereal Foods World 26: 75.

PAULSEN, M.R., and HILL, L.D. 1985. Corn Quality Factors Affecting Dry Milling Performance. J. Agric Eng Res., 31: 255.

PEPLINSKI, A.J., PAULSEN, M.R., ANDERSON, R.A., and KWOLEK, W.F. 1989. Physical, Chemical, and Dry-Milling Characteristics of Corn Hybrids from Various Genotypes. Cereal Chem., 66 (2): 117.

POMERANZ, Y., and CZUCHAJOWSKA, Z. 1985. Structure of coarse and fine fractions of corn samples ground on the Stenvert hardness tester. Food Microstructure, 4 (2): 213.

POMERANZ, Y., and CZUCHAJOWSKA, Z. 1987. Laboratory Tests to Predict the Commercial Yield of Flaking or Large Grits in Dry Corn Milling. J.Food Sci., 52 (3): 830, 832.

POMERANZ, Y., CZUCHAJOWSKA, Z., and LAI, F.S. 1986a. Gross Comparison of Course and Fine Fractions of Small Corn Samples Ground in the Stenvert Hardness Tester. Cereal Chem., 63 (1): 22.

POMERANZ, Y., CZUCHAJOWSKA, Z., and LAI, F.S. 1986b. Comparison of Methods for Determination of Hardness and Breakage Susceptability of Commercially Dried Corn. Cereal Chem., 63 (1): 39.

POMERANZ, Y., CZUCHAJOWSKA, Z., MARTIN, C.R., and LAI, F.S. 1985. Determination of Corn Hardness by the Stenvert Hardness Tester. Cereal Chem., 62: 108.

POMERANZ, Y., MARTIN, C.R., TRAYLOR, D.D., and LAI, F.S. 1984. Corn Hardness Determination. Cereal Chem., 61: 147.

REDDING, C.D., HURBURGH, C.R., JOHNSON, L.A., and FOX, S.R. 1990. Adjustment of Maize Quality Data for Moisture Content. Cereal Chem., 67 (3): 292.

ROONEY, L.W., SERNA-SALDIVAR, S.O. 1987. Food Uses of Whole Corn and Dry-Milled Fractions. In Corn: Chemistry and Technology, ed. WATSON, S.A., and RAMSTAD, P.E., 399. American Association of Cereal Chemists, Inc., St. Paul, MN.

ROSKENS, A.B. 1991. Personal communication. USGP Purchasing, Barrington, IL.

SINGH, S.S. and FINNER, M.F. 1983. A centrifugal impactor for damage susceptibility evaluation of shelled corn. Trans. ASAE 26: 1858.

SNEDECOR, G.W. and COCHRAN, W.G. 1980. Statistical Methods. 7th ed. The Iowa State University Press, Ames, IA.

STENVERT, N.L. 1974. Grinding resistance, a simple measure of wheat hardness. Flour Anim. Feed Milling 12: 24.

STROSHINE, R.L., KIRLEIS, A.W., TUITE, J.F., BAUMAN, L.F., and EMAM, A. 1986. Differences in Grain Quality Among Selected Hybrids. Cereal Foods World, 31 (4): 311.

THOMPSON, R.A., and ISAACS, G.W. 1967. Porosity determinations of grains and seeds in an air-comparison pycnometer. Trans. ASAE 10: 693.

WATSON, S.A. 1987. Measurement and Maintenance of Quality. In Corn: Chemistry and Technology, ed. WATSON, S.A., and RAMSTAD, P.E., 125. American Association of Cereal Chemists, Inc., St. Paul, MN.

USDA. 1990. Situation and Outlook Report Feed. FdS-316. U.S. Dep. Agric., Econ. Res. Serv. (Nov).

USDA. 1991. Agricultural Statistics. U.S. Dep. Agric., Washington, DC.

WOLF, M.J., BUZAN, C.L., MACMASTERS, M.M., and RIST, C.E. 1952. Structure of the Mature Corn Kernel. I. Gross Anatomy and Structural Relationships. Cereal Chemistry, 29 (5): 321.

ZUBER, M.S., and DARRAH, L.L., 1987. Breeding, Genetics, and Seed Corn Production. In Corn: Chemistry and Technology, ed. WATSON, S.A., and RAMSTAD, P.E., 31. American Association of Cereal Chemists, Inc. St. Paul, MN.

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APPENDIX A. A SURVEY OF CORN DRY MILLERS

A list of U.S. dry corn mills was obtained (Milling Directory, 1990). Dry mills in the Midwest area were selected for communication.

A letter was sent to each mill selected inquiring about their methods used for grading the hardness of corn to be purchased, and explaining the nature of this research. A response form was also included.

Of the 20 letters sent, there were 12 replies. Of these, three reported that they did not test the corn at purchase, and one mill was out of business. The remaining eight reported tests which included test weight, moisture, sizing, damaged kernel, foreign material, x-ray, aflatoxin, and mould. Three of these responses also reported testing for hardness. One company used the Stein breakage test, one used visual grading, and the other used a proprietary method. The latter two plus a third expressed interest in developing corn hardness tests.

APPENDIX B. DATA FROM DATA SET A

Table B1. Data set A

CASE	SAMP	HES	IDEN	HRW	HRG	AG3GB	AG3GR	AG3GY	AG3WB
1	1	48.2	72.2	55.03	69.03	34.70	82.70	76.83	13.33
2	124	51.9	74.1	52.90	69.20	34.23	84.13	76.90	11.42
3	125	47.6	71.7	52.00	67.77	35.17	79.12	73.80	12.17
4	132	49.2	72.4	47.30	70.13	34.72	85.47	75.80	9.920
5	133	49.0	73.1	52.60	69.23	35.20	85.47	76.70	10.50
6	241	61.0	76.5	46.80	67.47	28.75	81.88	71.75	9.500
7	303	63.9	81.3	51.27	69.43	29.62	80.72	74.78	11.42
8	316	60.9	77.8	51.27	70.20	36.63	83.73	76.87	10.42
9	335	59.2	77.4	53.07	70.30	33.47	81.53	74.87	12.83
10	386	53.2	77.3	53.63	70.17	35.72	84.50	77.80	11.67
11	393	49.9	73.1	56.67	69.50	39.67	86.50	80.55	13.08
12	395	56.6	78.1	54.43	70.43	35.28	84.00	76.88	12.08
13	455	47.8	73.2	59.17	73.40	39.55	86.00	80.72	13.25
14	459	57.2	77.5	57.10	70.93	30.93	87.87	78.20	13.00
15	461	61.2	79.1	53.57	70.60	30.40	85.70	78.10	11.42
16	472	57.3	73.9	56.37	70.63	33.50	82.33	77.02	13.08
17	508	60.3	80.6	48.40	65.13	25.47	74.40	68.35	11.42
18	526	51.1	77.1	52.80	70.90	35.97	84.08	78.92	11.33
19	541	46.5	75.7	53.90	70.69	35.03	86.12	77.58	11.42
20	550	54.7	78.4	51.70	69.20	33.00	87.97	77.83	11.08
21	562	57.8	70.4	53.87	69.03	35.70	81.03	74.33	12.17
22	587	62.7	77.1	57.63	69.87	34.50	85.13	78.97	13.42
23	905	51.1	74.9	56.77	70.60	34.00	85.40	79.00	12.17
24	907	56.5	79.4	48.43	68.10	33.45	82.55	73.23	8.920
25	929	52.2	76.0	53.13	69.50	31.25	81.25	72.50	12.66
26	930	57.1	76.9	50.17	67.67	35.47	80.27	73.73	10.75
27	955	62.7	82.4	47.17	68.53	28.80	81.00	73.03	10.42
28	961	58.0	77.3	45.53	66.03	32.03	81.63	73.02	8.080
29	978	43.0	72.5	59.87	70.78	38.30	85.20	80.25	13.53
30	985	39.7	73.4	60.10	72.63	38.30	88.17	81.92	14.92

Table B1. Data set A (contd.)

CASE	AG3WR	AG3WY	AG5GB	AG5GR	AG5GY	AG5WB	AG5WR	AG5WY
1	54.83	43.33	35.00	86.05	82.30	11.58	62.42	51.25
2	50.17	39.42	35.45	88.05	82.80	9.420	61.33	49.33
3	50.92	40.00	35.40	81.10	78.00	9.330	57.00	44.92
4	47.08	35.17	37.30	82.30	80.40	8.750	54.17	42.33
5	49.42	38.33	37.85	83.75	80.55	9.250	57.58	47.69
6	46.33	33.41	28.05	80.70	75.70	7.920	52.08	38.75
7	49.33	38.50	28.95	84.90	79.70	10.07	55.98	45.50
8	50.58	39.50	32.60	87.00	81.70	8.330	60.33	47.83
9	53.42	42.33	33.55	84.95	81.50	11.08	61.25	49.50
10	55.33	44.33	37.05	88.90	83.10	10.17	65.08	58.67
11	58.08	47.08	40.45	90.65	85.95	12.25	71.08	58.50
12	56.00	44.50	36.10	88.43	82.60	10.67	65.08	53.42
13	60.33	49.25	41.50	85.45	86.35	12.17	67.08	56.00
14	51.25	42.17	34.40	90.45	86.05	14.25	64.28	54.17
15	52.25	42.17	33.90	87.70	84.65	10.67	61.75	46.42
16	62.42	52.92	33.05	88.85	84.60	13.08	62.42	52.92
17	42.42	35.25	24.65	80.40	76.15	10.58	48.33	40.67
18	54.08	42.08	35.95	90.55	86.10	10.17	61.08	48.17
19	49.50	39.33	37.90	82.05	80.50	10.58	60.67	50.25
20	52.42	40.33	35.85	88.40	83.25	9.670	62.08	45.17
21	53.42	42.08	39.80	84.40	80.90	11.08	60.42	49.33
22	60.42	50.00	36.05	90.95	86.50	12.92	69.83	57.92
23	59.33	48.08	35.20	89.50	86.10	14.00	67.42	57.08
24	50.33	37.83	35.50	84.15	80.90	8.250	58.25	46.33
25	54.42	43.25	33.55	85.25	80.20	6.580	59.75	48.92
26	48.66	36.33	35.25	83.10	79.55	10.00	57.42	45.20
27	44.92	33.25	29.05	83.35	78.70	8.250	53.17	40.25
28	45.58	30.67	32.95	84.65	78.50	8.080	51.92	37.58
29	58.42	49.08	39.05	87.25	84.85	13.83	70.60	60.08
30	61.17	51.67	39.60	92.05	88.40	14.75	73.67	62.92

Table B1. Data set A (contd.)

CASE	NIRO	NIRP	NIRS	NIRW	H2O
1	3.373	8.807	58.66	8.967	14.2
2	2.990	8.027	58.02	9.047	15.8
3	2.973	8.217	58.22	9.617	16.8
4	2.670	8.550	58.08	10.18	15.6
5	3.063	7.703	58.40	9.213	14.7
6	3.213	8.817	56.83	8.173	15.8
7	2.857	9.177	55.63	8.170	17.2
8	2.683	8.000	56.87	9.083	15.8
9	3.050	7.783	58.08	9.340	15.8
10	2.860	8.023	57.89	9.520	15.4
11	2.887	6.907	58.62	9.717	15.5
12	3.087	6.757	58.63	9.177	15.7
13	2.897	6.867	58.60	9.590	16.2
14	3.087	9.010	57.34	8.683	14.8
15	2.783	8.587	57.00	9.147	15.4
16	3.043	8.313	57.57	8.850	15.3
17	4.653	9.400	58.86	6.680	14.1
18	2.907	7.740	58.33	9.690	13.3
19	2.887	8.153	57.98	9.370	14.1
20	2.873	7.780	57.76	9.230	15.1
21	2.797	8.847	58.26	10.14	14.1
22	2.937	7.370	58.28	9.250	13.4
23	2.967	7.203	57.99	9.130	15.7
24	3.103	7.880	57.90	M	14.7
25	2.757	8.230	57.23	9.193	14.1
26	2.890	6.017	57.77	M	14.2
27	2.867	7.980	56.74	8.603	15.7
28	3.103	7.670	57.64	8.720	15.3
29	2.943	6.410	59.08	10.05	18.6
30	2.893	6.623	58.91	9.997	18.4

Table B2. Correlation matrix for data set A

	HES	IDEN	NIRO	NIRP	NIRS	HRG	HRW
IDEN	0.7006						
NIRO	0.1555	0.2285					
NIRP	0.4173	0.2040	0.3304				
NIRS	-0.6562	-0.5675	0.3017	-0.4488			
HRG	-0.4323	-0.2889	-0.5535	-0.3424	0.1481		
HRW	-0.5002	-0.4563	-0.2041	-0.4053	0.4502	0.7581	
AG3GB	-0.6634	-0.6623	-0.5064	-0.6816	0.5517	0.5923	0.5997
AG3GR	-0.4399	-0.2585	-0.5674	-0.3711	0.1532	0.7347	0.5504
AG3GY	-0.5329	-0.3847	-0.4974	-0.5122	0.3351	0.8407	0.8068
AG3WB	-0.4170	-0.3993	-0.0338	-0.2345	0.4264	0.6070	0.8959
AG3WR	-0.4028	-0.4437	-0.3364	-0.4845	0.3869	0.7250	0.8790
AG3WY	-0.4012	-0.4118	-0.2081	-0.3985	0.4140	0.7240	0.9299
AG5GB	-0.6889	-0.6859	-0.5394	-0.5691	0.5672	0.6169	0.6165
AG5GR	-0.1664	-0.0677	-0.3171	-0.3659	0.1772	0.5986	0.6788
AG5GY	-0.3817	-0.2616	-0.3625	-0.4505	0.3414	0.8013	0.8354
AG5WB	-0.3323	-0.3121	0.0624	-0.2957	0.4444	0.5457	0.8308
AG5WR	-0.4833	-0.3849	-0.3812	-0.5761	0.4345	0.7524	0.9140
AG5WY	-0.5062	-0.3996	-0.2438	-0.4898	0.4742	0.7243	0.9299

	AG3GB	AG3GR	AG3GY	AG3WB	AG3WR	AG3WY	AG5GB
AG3GR	0.5429						
AG3GY	0.7387	0.8612					
AG3WB	0.4051	0.2852	0.5802				
AG3WR	0.6431	0.5077	0.7643	0.7683			
AG3WY	0.5667	0.4594	0.7414	0.8560	0.9717		
AG5GB	0.8980	0.6677	0.7396	0.3983	0.6096	0.5400	
AG5GR	0.4239	0.6528	0.7762	0.5391	0.7307	0.7107	0.4127
AG5GY	0.5950	0.7517	0.9142	0.6549	0.8318	0.8271	0.6276
AG5WB	0.3720	0.4277	0.6720	0.7660	0.6900	0.7670	0.3901
AG5WR	0.7129	0.6994	0.8887	0.7617	0.8957	0.8873	0.7095
AG5WY	0.6673	0.5773	0.8081	0.8059	0.8754	0.9044	0.6524

	AG5GR	AG5GY	AG5WB	AG5WR
AG5GY	0.9006			
AG5WB	0.6064	0.7448		
AG5WR	0.8091	0.8994	0.7389	
AG5WY	0.7364	0.8339	0.7747	0.9522

CASES INCLUDED 30 MISSING CASES 0

Table B3. Regression analysis and analysis of variance for Equation 1

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF HES

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P	VIF
CONSTANT	-62.8721	20.0656	-3.13	0.0041	
IDEN	1.32172	0.26554	4.98	0.0000	1.0
NIRP	2.10635	0.94926	2.22	0.0351	1.0

R-SQUARED	0.5693	RESID. MEAN SQUARE (MSE)	17.8990
ADJUSTED R-SQUARED	0.5374	STANDARD DEVIATION	4.23072

SOURCE	DF	SS	MS	F	P
REGRESSION	2	638.843	319.422	17.85	0.0000
RESIDUAL	27	483.272	17.8990		
TOTAL	29	1122.12			

CASES INCLUDED 30 MISSING CASES 0

STEPWISE ANALYSIS OF VARIANCE OF HES

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOWS' CP	P
CONSTANT	88291.9						
IDEN	550.714	1	550.714	550.714	0.4726	5.9	2
NIRP	88.1289	2	638.843	319.422	0.5374	3.0	3
RESIDUAL	483.272	29	1122.12	38.6936			

R-SQUARED	0.5693	RESID. MEAN SQUARE (MSE)	17.8990
ADJUSTED R-SQUARED	0.5374	STANDARD DEVIATION	4.23072

Table B4. Regression analysis and analysis of variance for Equation 2

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF HES

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P	VIF
CONSTANT	398.562	60.8815	6.55	0.0000	
NIRO	6.99081	2.38533	2.93	0.0068	1.1
NIRS	-6.30862	1.08199	-5.83	0.0000	1.1

R-SQUARED	0.5680	RESID. MEAN SQUARE (MSE)	17.9521
ADJUSTED R-SQUARED	0.5360	STANDARD DEVIATION	4.23699

SOURCE	DF	SS	MS	F	P
REGRESSION	2	637.409	318.705	17.75	0.0000
RESIDUAL	27	484.706	17.9521		
TOTAL	29	1122.12			

CASES INCLUDED 30 MISSING CASES 0

STEPWISE ANALYSIS OF VARIANCE OF HES

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOWS' CP	P
CONSTANT	88291.9						
NIRO	27.1158	1	27.1158	27.1158	-0.0107	35.0	2
NIRS	610.293	2	637.409	318.705	0.5360	3.0	3
RESIDUAL	484.706	29	1122.12	38.6936			

R-SQUARED	0.5680	RESID. MEAN SQUARE (MSE)	17.9521
ADJUSTED R-SQUARED	0.5360	STANDARD DEVIATION	4.23699

Table B5. Regression analysis and analysis of variance for Equation 3

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF HES

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P	VIF
CONSTANT	266.157	67.0559	3.97	0.0005	
NIRS	-3.19234	1.23727	-2.58	0.0156	1.5
AG5GB	-0.77223	0.25092	-3.08	0.0047	1.5

R-SQUARED	0.5785	RESID. MEAN SQUARE (MSE)	17.5178
ADJUSTED R-SQUARED	0.5473	STANDARD DEVIATION	4.18543

SOURCE	DF	SS	MS	F	P
REGRESSION	2	649.134	324.567	18.53	0.0000
RESIDUAL	27	472.981	17.5178		
TOTAL	29	1122.12			

CASES INCLUDED 30 MISSING CASES 0

STEPWISE ANALYSIS OF VARIANCE OF HES

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOWS' CP	P
CONSTANT	88291.9						
NIRS	483.214	1	483.214	483.214	0.4103	10.5	2
AG5GB	165.920	2	649.134	324.567	0.5473	3.0	3
RESIDUAL	472.981	29	1122.12	38.6936			

R-SQUARED	0.5785	RESID. MEAN SQUARE (MSE)	17.5178
ADJUSTED R-SQUARED	0.5473	STANDARD DEVIATION	4.18543

APPENDIX C. DATA FROM DATA SET B

Table C1. Data set B

CASE	SAMP	DEN	HARD	TEX	IOOKV	IOOKW	NITO	NITP	NITS
1	571	1.207	80	388.8	30	38.4	3.22	9.11	59.46
2	563	1.209	80	400.2	30	38.1	3.00	8.60	60.32
3	739	1.309	80	393.6	26	35.8	3.11	8.35	60.75
4	742	1.258	85	435.2	26	34.5	3.33	8.50	59.99
5	747	1.218	85	425.8	25	32.3	3.32	9.34	59.19
6	555	1.249	80	386.0	27	35.4	3.49	6.48	62.64
7	177	1.259	72	407.0	26	34.6	2.86	7.03	62.34
8	161	1.240	80	360.8	26	34.0	3.29	7.10	62.40
9	203	1.167	70	331.2	29	35.9	3.23	6.92	62.95
10	204	1.190	85	347.4	25	31.1	3.20	6.68	63.33
11	111	1.240	85	403.0	29	37.6	3.25	6.61	62.85
12	112	1.203	85	454.8	27	33.6	3.31	7.60	60.82
13	121	1.294	90	419.8	26	34.6	3.08	7.70	60.62
14	251	1.273	82	379.8	27	35.4	3.43	6.30	63.09
15	252	1.233	82	475.8	30	38.2	3.38	6.80	62.15
16	421	1.244	95	462.2	30	38.5	3.52	7.12	62.06
17	422	1.246	90	397.8	26	33.2	3.23	7.78	61.02
18	423	1.260	92	487.0	31	39.1	3.71	8.23	61.11
19	201	1.184	85	444.6	28	35.7	3.00	9.06	59.55
20	202	1.283	82	411.2	26	36.1	3.01	8.67	59.98
21	203	1.225	92	446.0	28	36.9	3.36	8.53	60.16
22	204	1.246	75	362.2	25	33.3	3.13	7.54	61.51
23	206	1.194	80	390.8	29	37.3	3.37	7.38	61.49
24	210	1.233	85	402.8	26	34.8	3.43	8.15	60.94
25	212	1.175	90	405.0	27	34.2	3.14	8.12	60.86
26	214	1.225	80	396.2	27	34.8	3.28	7.88	61.07
27	218	1.225	82	417.4	25	32.9	3.30	7.87	61.11
28	219	1.245	85	436.2	26	34.8	3.34	9.08	59.44
29	220	1.254	85	387.2	27	36.6	3.50	7.75	61.31
30	221	1.283	82	388.0	23	32.1	3.18	6.85	62.19
31	222	1.254	82	382.2	26	35.1	3.10	8.00	60.69
32	223	1.274	82	360.8	25	34.3	3.14	6.85	62.42
33	224	1.206	75	463.2	29	37.4	3.40	7.01	62.23
34	646	1.173	75	374.8	27	34.4	3.65	7.72	61.73
35	647	1.183	80	294.6	24	30.8	3.31	6.65	63.24
36	649	1.161	95	344.0	25	31.8	3.17	7.27	62.21
37	41	1.216	75	373.8	25	32.5	3.59	9.47	58.51
38	42	1.226	80	410.2	25	32.6	3.56	10.08	57.67
39	43	1.205	75	492.6	28	36.4	3.74	9.70	57.91
40	45	1.266	80	486.0	26	35.1	3.95	9.49	58.17
41	46	1.246	75	365.6	26	34.7	3.53	9.62	58.56
42	48	1.226	80	394.2	25	32.9	3.63	10.67	56.69
43	52	1.204	80	453.0	28	36.4	3.42	10.16	57.55
44	53	1.254	90	404.8	25	33.8	3.72	9.61	58.14
45	54	1.257	90	493.8	27	36.2	3.53	9.13	58.76
46	55	1.215	80	423.6	26	33.9	3.57	10.23	57.20
47	56	1.226	80	389.0	25	32.7	3.44	9.56	58.39
48	57	1.246	80	431.8	25	33.1	3.40	11.52	55.94

Table C1. Data set B (Contd.)

CASE	NITW	THINS	H2O
1	7.75	2.5	11.0
2	7.15	2.5	11.7
3	6.91	16.4	11.6
4	6.70	10.8	11.4
5	7.20	12.2	11.2
6	6.90	39.9	11.8
7	6.51	39.9	11.6
8	6.04	35.5	12.0
9	7.01	35.3	11.0
10	6.76	34.6	12.0
11	7.32	21.8	12.2
12	8.16	33.0	13.2
13	7.59	22.8	13.5
14	7.26	41.6	13.2
15	7.57	23.2	13.0
16	6.99	31.3	13.5
17	7.13	35.2	14.0
18	6.77	12.1	15.4
19	6.26	59.4	10.0
20	6.65	33.8	9.6
21	6.56	30.5	10.4
22	6.85	39.2	10.5
23	6.88	31.8	10.0
24	6.64	51.2	9.6
25	6.24	49.9	10.2
26	6.92	42.1	10.2
27	6.68	57.7	10.4
28	6.53	55.8	10.3
29	6.62	45.4	9.8
30	6.46	49.0	9.6
31	6.42	62.8	9.9
32	6.76	48.9	10.0
33	6.18	32.9	10.5
34	6.28	62.4	9.6
35	7.00	77.0	9.6
36	6.41	71.9	9.0
37	8.66	7.4	10.6
38	8.15	3.9	10.8
39	8.85	3.4	10.4
40	9.21	3.2	10.7
41	8.44	6.0	10.6
42	9.00	12.3	10.6
43	8.74	12.5	10.0
44	8.88	4.3	10.0
45	8.53	4.7	11.0
46	8.96	3.4	10.2
47	8.99	7.6	10.6
48	8.48	8.9	10.8

APPENDIX D. DATA FROM DATA SET C

Table D1. Expanded data set C

CASE	SAMP	YFG	PDEN	DEN	NITO	NITP	NITS	NIRO
1	1	35.5	1.343	1.275	3.69	10.12	57.70	3.60
2	2	35.2	1.333	1.285	3.64	10.33	57.47	2.42
3	3	27.7	1.330	1.222	3.50	9.39	58.43	3.05
4	4	30.7	1.312	1.262	3.47	9.31	58.43	3.45
5	5	26.9	1.324	1.229	3.59	11.12	56.75	3.35
6	6	29.1	1.315	1.270	3.57	9.45	58.97	3.42
7	7	22.3	1.282	1.197	3.47	9.15	59.72	2.98
8	8	25.7	1.311	1.222	3.65	10.22	58.12	2.93
9	9	24.6	1.286	1.226	3.79	8.39	60.41	3.60
10	10	20.2	1.276	1.217	3.78	9.00	59.22	3.29
11	11	23.3	1.287	1.213	3.88	8.60	59.81	3.62
12	12	14.3	1.257	1.192	3.59	9.52	58.59	3.21
13	13	12.1	1.251	1.195	3.76	7.96	59.80	3.31
14	14	6.3	1.231	1.171	3.75	7.72	60.33	3.37
15	1	22.6	1.279	M	4.27	7.09	62.29	M
16	2	18.1	1.275	M	4.12	6.63	62.30	M
17	3	18.0	1.282	M	4.06	6.74	62.35	M
18	4	16.5	1.247	M	4.03	7.71	60.67	M
19	5	15.4	1.250	M	4.00	6.40	62.67	M
20	6	13.1	1.251	M	4.12	7.04	61.99	M
21	7	9.6	1.221	M	4.13	7.17	61.47	M
22	8	9.3	1.219	M	3.92	6.81	61.65	M
23	9	5.3	1.220	M	3.95	6.74	61.39	M

M indicates a missing value.
Samples 1 through 14 are the original data set C.

Table D1. Expanded data set C (Contd.)

CASE	NIRP	NIRS	AG3B	AG3G	AG3R	AG3Y	INST	THINS
1	9.59	56.83	9.20	33.83	55.17	47.17	287.3	58.2
2	10.50	57.41	9.07	32.57	54.93	44.33	189.2	51.2
3	8.59	58.95	9.83	34.63	57.30	47.80	189.0	51.3
4	8.34	58.92	9.13	36.17	60.37	51.00	221.9	27.8
5	9.77	57.52	9.63	35.47	59.60	49.53	188.2	50.0
6	8.47	58.17	9.80	33.80	59.67	48.87	198.8	47.5
7	8.03	59.81	8.97	33.00	56.70	45.57	136.5	47.1
8	9.22	58.62	9.23	32.93	58.00	47.07	196.0	40.7
9	7.29	59.78	10.53	39.13	63.83	54.33	171.4	24.2
10	8.53	58.80	10.17	39.67	63.27	53.67	181.4	35.0
11	7.72	59.39	10.67	39.97	64.47	55.10	211.6	25.4
12	7.81	59.70	8.93	35.67	62.10	50.47	149.5	36.6
13	6.36	61.41	11.83	43.00	67.60	58.47	119.5	46.3
14	6.40	60.89	11.53	42.63	66.47	56.63	102.5	53.3
15	M	M	10.50	34.60	60.30	48.80	148.4	48.1
16	M	M	9.00	33.80	58.80	47.20	166.2	75.8
17	M	M	9.00	33.30	58.00	47.90	159.0	65.0
18	M	M	9.40	34.20	62.00	50.20	161.1	6.9
19	M	M	12.00	37.00	62.50	51.80	165.4	32.0
20	M	M	9.80	34.30	60.40	48.90	130.0	72.7
21	M	M	13.80	42.50	68.70	58.10	122.0	12.0
22	M	M	13.50	44.80	68.50	59.20	112.7	28.3
23	M	M	12.00	43.50	68.10	58.50	129.9	63.4

M indicates a missing value.
Samples 1 through 14 are the original data set C.

Table D2. Correlation matrix for data set C.

	YFG	ILHD	PDEN	DEN	NITO	NITP	NITS
ILHD	0.8817						
PDEN	0.9607	0.9094					
DEN	0.9135	0.8086	0.8428				
NITO	-0.3405	-0.5870	-0.3929	-0.2515			
NITP	0.6940	0.6799	0.7793	0.5787	-0.4671		
NITS	-0.6385	-0.7157	-0.7500	-0.5880	0.4497	-0.9434	
NIRO	-0.1757	-0.2857	-0.2043	-0.1354	0.3723	-0.3733	0.3641
NIRP	0.8262	0.7760	0.8635	0.7375	-0.3478	0.9249	-0.8795
NIRS	-0.8648	-0.7851	-0.8899	-0.8181	0.2557	-0.8611	0.8164
AG3B	-0.6522	-0.6335	-0.6218	-0.5124	0.6695	-0.7735	0.6518
AG3G	-0.7392	-0.7342	-0.7581	-0.5962	0.6852	-0.8060	0.6726
AG3R	-0.8050	-0.8539	-0.8315	-0.6516	0.6102	-0.7813	0.6964
AG3Y	-0.7159	-0.7582	-0.7399	-0.5662	0.6629	-0.7846	0.6679
INST	0.8385	0.6744	0.8139	0.7756	-0.0701	0.5612	-0.5550
THINS	0.0824	0.4023	0.2456	0.1271	-0.2901	0.3100	-0.4048

	NIRO	NIRP	NIRS	AG3B	AG3G	AG3R	AG3Y
NIRP	-0.4629						
NIRS	0.1681	-0.9391					
AG3B	0.3984	-0.7447	0.6765				
AG3G	0.4996	-0.7970	0.7265	0.9111			
AG3R	0.5085	-0.8492	0.7869	0.8440	0.9455		
AG3Y	0.6005	-0.8184	0.7197	0.8839	0.9785	0.9755	
INST	0.2251	0.6594	-0.8141	-0.5029	-0.4958	-0.5748	-0.4404
THINS	-0.3593	0.3035	-0.2824	-0.0680	-0.2987	-0.4303	-0.3964

	INST
THINS	-0.0191

CASES INCLUDED 14   MISSING CASES 0

Table D3. Regression analysis and analysis of variance for Equation 4

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF YFG

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	-285.217	25.7927	-11.06	0.0000
PDEN	238.544	19.9012	11.99	0.0000

R-SQUARED	0.9229	RESID. MEAN SQUARE (MSE)	5.92251
ADJUSTED R-SQUARED	0.9165	STANDARD DEVIATION	2.43362

SOURCE	DF	SS	MS	F	P
REGRESSION	1	850.913	850.913	143.67	0.0000
RESIDUAL	12	71.0701	5.92251		
TOTAL	13	921.984			

CASES INCLUDED 14 MISSING CASES 0

STEPWISE ANALYSIS OF VARIANCE OF YFG

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOWS' CP	P
CONSTANT	7961.93						
PDEN	850.913	1	850.913	850.913	0.9165	2.0	2
RESIDUAL	71.0701	13	921.984	70.9218			

R-SQUARED	0.9229	RESID. MEAN SQUARE (MSE)	5.92251
ADJUSTED R-SQUARED	0.9165	STANDARD DEVIATION	2.43362

Table D4. Regression analysis and analysis of variance for Equation 5

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF YFG

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P	VIF
CONSTANT	-292.811	22.3697	-13.09	0.0000	
PDEN	248.509	17.6110	14.11	0.0000	1.1
THINS	-0.12518	0.05434	-2.30	0.0417	1.1

R-SQUARED	0.9480	RESID. MEAN SQUARE (MSE)	4.35809
ADJUSTED R-SQUARED	0.9386	STANDARD DEVIATION	2.08760

SOURCE	DF	SS	MS	F	P
REGRESSION	2	874.045	437.022	100.28	0.0000
RESIDUAL	11	47.9390	4.35809		
TOTAL	13	921.984			

CASES INCLUDED 14 MISSING CASES 0

STEPWISE ANALYSIS OF VARIANCE OF YFG

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOWS' CP	P
CONSTANT	7961.93						
PDEN	850.913	1	850.913	850.913	0.9165	6.3	2
THINS	23.1311	2	874.045	437.022	0.9386	3.0	3
RESIDUAL	47.9390	13	921.984	70.9218			

R-SQUARED	0.9480	RESID. MEAN SQUARE (MSE)	4.35809
ADJUSTED R-SQUARED	0.9386	STANDARD DEVIATION	2.08760

Table D5. Regression analysis and analysis of variance for Equation 6

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	-261.165	17.0416	-15.33	0.0000
PDEN	220.146	13.3340	16.51	0.0000

R-SQUARED	0.9285	RESID. MEAN SQUARE (MSE)	5.67047
ADJUSTED R-SQUARED	0.9251	STANDARD DEVIATION	2.38128

SOURCE	DF	SS	MS	F	P
REGRESSION	1	1545.68	1545.68	272.58	0.0000
RESIDUAL	21	119.080	5.67047		
TOTAL	22	1664.76			

CASES INCLUDED 23 MISSING CASES 0

STEPWISE ANALYSIS OF VARIANCE OF YFG

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOWS' CP	P
CONSTANT	9268.13						
PDEN	1545.68	1	1545.68	1545.68	0.9251	2.0	2
RESIDUAL	119.080	22	1664.76	75.6709			

R-SQUARED	0.9285	RESID. MEAN SQUARE (MSE)	5.67047
ADJUSTED R-SQUARED	0.9251	STANDARD DEVIATION	2.38128

Table D6. Regression analysis and analysis of variance for Equation 7

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF YFG

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P	VIF
CONSTANT	-268.034	13.7040	-19.56	0.0000	
PDEN	228.364	10.8592	21.03	0.0000	1.0
THINS	-0.08359	0.02309	-3.62	0.0017	1.0

R-SQUARED	0.9568	RESID. MEAN SQUARE (MSE)	3.59658
ADJUSTED R-SQUARED	0.9525	STANDARD DEVIATION	1.89647

SOURCE	DF	SS	MS	F	P
REGRESSION	2	1592.83	796.414	221.44	0.0000
RESIDUAL	20	71.9317	3.59658		
TOTAL	22	1664.76			

CASES INCLUDED 23   MISSING CASES 0

STEPWISE ANALYSIS OF VARIANCE OF YFG

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOWS' CP	P
CONSTANT	9268.13						
PDEN	1545.68	1	1545.68	1545.68	0.9251	14.1	2
THINS	47.1483	2	1592.83	796.414	0.9525	3.0	3
RESIDUAL	71.9317	22	1664.76	75.6709			

R-SQUARED	0.9568	RESID. MEAN SQUARE (MSE)	3.59658
ADJUSTED R-SQUARED	0.9525	STANDARD DEVIATION	1.89647

APPENDIX E. TESTING THE PROPOSED MODELS

Prediction tests were carried out using the data that was used to generate the equations in data set C. The predicted values for Equations 4 and 5, and actual yields are reported in Table E1.

Table E1. Yield prediction using data used to generate Equations 4 and 5.

Sample #	Actual Yield	Predicted Yield	
		Equation 4	Equation 5
1	35.5	36.1	34.2
2	35.2	33.7	32.6
3	27.7	32.8	31.7
4	30.7	28.5	30.1
5	26.9	31.5	30.5
6	29.1	29.3	28.5
7	22.3	21.5	20.4
8	25.7	28.3	28.3
9	24.6	22.5	24.3
10	0.2	20.1	20.5
11	3.3	22.6	24.3
12	4.3	15.3	15.3
13	2.1	14.0	12.7
14	6.3	9.2	6.8

A sample of nine hybrids of corn harvested in 1992 was selected, containing a range of hardnesses. These samples were milled and tested according to the methods described for data set C. (Raw Data appears in Table D1, sample I.D.'s 15 through 23.) The results from the tests were entered into Equations 4 and 5, and compared with actual yields. The results are shown in Table E2.

Table E2. Results from 1992 harvest corn.

Sample #	Actual Yield	Predicted Yield	
		Equation 4[a]	Equation 5[b]
1	22.6	20.7	19.5
2	18.1	19.7	15.0
3	18.0	21.4	18.1
4	16.5	13.0	16.6
5	15.4	13.8	14.3
6	13.1	14.0	9.4
7	9.6	6.8	9.5
8	9.3	6.3	7.0
9	5.3	6.6	2.9

[a]Std. Dev. for predicted values = 2.32
[b]Std. Dev. for predicted values = 1.56